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Oxyfuel combustion: technical and economic considerations for the development of carbon capture from pulverized coal power plants

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Abstract

Oxyfuel has been hoped by many to provide the "step-change" in performance needed to drive down the avoidance cost of carbon capture from pulverized coal plants. To investigate this possibility, a techno-economic oxyfuel model was constructed. The model was exercised to explore the effect on CO2 avoidance cost and LCOE from several key parameters, namely: CO2 purity, oxidant purity, CPU and ASU performance and cost, coal composition, and geographic location. Monte-Carlo techniques were then used to generate distributions for CO2 avoidance cost and LCOE which were compared to costs for a representative amine based post-combustion capture system. Results indicate that increasing restrictions on CO2 exit purity will translate directly to higher avoidance costs. Consequently, any future pipeline purity standards should seek to balance costs with safety concerns and storage capacity limitations. A trade-off between equipment downsizing and energy of separation for oxidant purity was identified and found to be optimized in the 95-97% oxygen range. The effect of oxidant purity on CO2 transport cost is small (~2%) compared to the effects of CO2 exit purity (~15%). Both represent changes to a cost which amounts to only about 5% of the total avoidance cost. Stochastic modeling results provide evidence that oxyfuel technology is unlikely to be competitive with post-combustion capture for a number of coal types, especially those high in sulfur. Oxyfuel appears most promising for use with low-sulfur coals and is capable of delivering lower avoidance costs than amine-based capture when operated with co-capture of SO2 and non-condensable gases.

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Keywords: CO2 Capture and storage; Oxyfuel; Avoidance cost; LCOE

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1. Introduction and objectives

Oxyfuel is one form of carbon dioxide capture and storage (CCS), a suite of technologies, which could potentially play a critical role in the mitigation of global climate change. Cost is currently the major impediment preventing the application of CCS to power generation stations and large industrial sources of CO2 [1-3]. Previous studies of the application of oxyfuel technology to pulverized coal power stations [4,5] had provided rationale for supposing that the technology may be capable of providing a "step change" reduction in the cost of CCS. Given the potential for large scale greenhouse gas reductions from CCS generally, information regarding potential cost reductions would be sought by a broad range of actors in government, industry and other organizations for purposes of policy analysis, investment decisions, technology assessments, R&D activities, and energy-environmental policy-making, including development of legislation and regulations involving CCS [6].

Our principal objectives in this paper are to: (1) develop a general techno-economic oxyfuel model capable of generating performance and cost estimates from a variety of physical and financial conditions; (2) explore a broad range of key assumptions which influence the performance and cost of the developed model to identify inflection points and trends in the results; and (3) contextualize the modeling results through comparison with a competing CCS technology and by extrapolating what the potential costs of widespread oxyfuel adoption may be for the United States. We conclude by discussing the implications of our results and by commenting on the potential for oxyfuel technology in light of potential advancements in associated system processes.

2. Model characterization and metrics for comparative assessment

The oxyfuel model created for this study was designed as a module of the Integrated Environmental Control Model (IECM) to be used for systematic, comparative evaluation of fossil fuel power systems. The IECM is a publicly available tool developed by Carnegie Mellon University for the US Department of Energy's National Energy Technology Laboratory (DOE/NETL) [7]. As with the pulverized coal base plant and Amine FG+ capture models; the oxyfuel model employs fundamental mass and energy balances, together with empirical data, to quantify overall plant performance, resource consumption, and emissions. Plant and component performance models are linked to a companion set of techno-economic and financial models which calculate capital and both fixed and variable operation and maintenance costs for each individual plant component plus the total levelized cost of electricity (LCOE) of the overall plant. Akin to other IECM modules, the oxyfuel model draws upon several detailed techno-economic performed by private companies, academics, and governmental organizations [8-16]. The generalized modeling tool produced is then calibrated to these case studies to produce consistent results given the same set of input assumptions.

In this paper we exercise the newly created oxyfuel model to explore the major factors which affect the relative costs and environmental impacts of carbon capture using oxyfuel combustion. The two major metrics used in this paper to evaluate performance are carbon dioxide avoidance cost and levelized cost of electricity as defined by Eq. 1 and Eq. 2, respectively.

$$LCOE = \frac{(TCC)(FCF)+(FOM)}{(CF)(8766)(MW)} + VOM \qquad (1)$$

$$Cost\ of\ CO_2\ Avoided\ \left[{}^{\$}/_{tCO_2}\right] = \frac{COE_{CCS} - COE_{REF}}{(tCO_2/MWh)_{REF} - (tCO_2/MWh)_{CCS}} \quad (2)$$

The base plants used in the above calculations were modeled using the IECM v8.0 and meet all emission level requirements for pulverized coal plants compatible with the new source performance standards. The Amine FG+ plants used in the stochastic model comparisons were also modeled using the IECM and their performance results are taken to be representative of post-combustion capture system performance for a 550MW-net plant with a levelized capacity factor of 75% [6].

2.1 Transport and storage model

Unlike post-combustion capture, the CO2 product leaving an oxyfuel plant is often impure. This leads to the need for special precautions when handling the mixture as well as a need to assess how the amount of inert impurities in the product affects the transportation system. Two-phase flow and the condensation of acid gases are the two main concerns when transporting impure CO2 product. Two-phase flow can cause pump failure due to cavitation and condensation of acid gases would either lead to increased levels of corrosion or the need for more expensive, corrosion resistant materials [17]. Work by Vattenfall [18] indicates that both issues can be prevented if the mixture is kept at a sufficiently high pressure to ensure that all components of the mixture remain as super-critical fluids for the duration of transport through the pipeline network.

With the required pressures known to allow for the safe transportation of impure CO2 product through an analogous transportation system designed for a post-combustion capture plant the transportation model developed by McCoy [19] was altered to accommodate the oxyfuel process. To modify the existing integrated performance and cost model it was necessary to alter the current model to accept gas mixtures produced by the oxyfuel process. The Peng-Robinson equations of state interaction parameters, and other property databases in the model, were updated to include argon. With these modifications completed a series of cases could be analyzed to determine the effects of oxidant and CO2 exit purity on transport cost. For each case it was necessary to define system entry conditions of the CO2 product, a minimum system exit pressure, and the distance from plant to sequestration site. The model could then calculate the required pipe diameter and associated costs necessary to transport the CO2 product, without booster pumps, whilst meeting the pressure constraints.

3. Model Results

To assess the performance and cost impacts associated with CO2 exit purity, ASU oxidant purity, and fuel variation the model was exercised in a parametric fashion to calculate LCOE and CO2 avoidance costs across the appropriate range for each parameter. Oxidant purity, CO2 exit purity, and distance between plant and sequestration site were then evaluated parametrically to assess their effect on the transportation system. Lastly, the oxyfuel and transport models were combined and evaluated stochastically for two representative coals, the results of which are presented relative to an analogous post-combustion capture system from the IECM.

3.1 The effects of CO2 exit purity

The exit purity of the CO2 product from the model was varied from 83-99.9%, a range representative of flue gas dehydration to dual distillation columns to remove inert gases. Six different coal types were used from the IECM to illustrate the range of avoidance costs which result from their use. From Fig. 1 it is clear that the low purity systems are currently the cheapest option. This is partly a consequence of lower capital intensity thanks to the foregone need to purify the flue gas combined with the low cost of fuel which does not provide adequate financial disincentive to avoid operating the plant at the slightly less thermally efficient, low purity state.

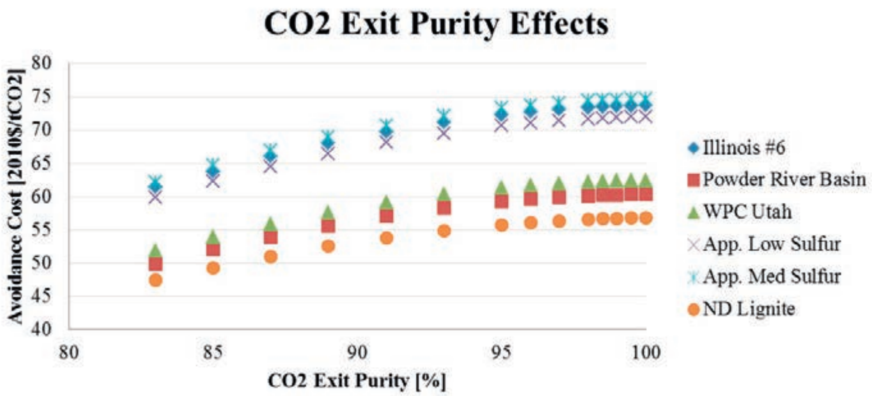

Fig.1. Cost of mitigation increases slightly more for more expensive coals as CO2 exit purity requirements are increased but the financially optimal strategy is to avoid additional flue gas processing if this option is geologically and legislatively available.

3.2 The effects of oxidant purity

Oxidant purity affects the model results by two different means. The primary effect is that in accordance with the relationship between purity and specific energy of separation the energy consumption of the ASU increases as desired oxidant purity is increased. The secondary, and contrary effect, is that as purity increases the total gas throughput of the plant is decreased and consequently the downstream components can be downsized. The interplay of these competing effects can be seen across coal types in Fig.2.

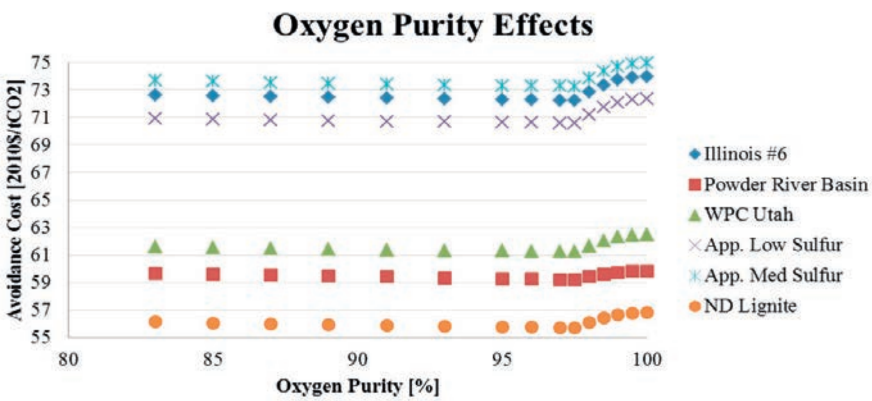

Fig.2. The effect of oxidant purity on mitigation cost is most pronounced for expensive coals where there is appreciable cost savings to be garnered from reducing ASU energy consumption.

As expected there is a prominent inflection point for all of the coals where the rapidly increasing energy penalty associated with removing argon from the oxidant begins to dominate the modest savings from component downsizing. The three higher sulfur content coals exhibit most strongly the economic impact of argon separation due to a combination of high energy cost relative to other coals and the need to perform extra flue gas processing to remove sulfur. What is also apparent from Fig. 2 is that the case studies performed by other parties have been justified in their selection of 95-96% oxygen purity as this represents the area where the trade-off between ASU specific separation energy and returns from equipment downsizing appears optimized.

3.3 The effect of oxygen purity and CO2 exit purity on transportation and storage costs

The parametric evaluations of oxidant purity and distance below employ the use of three purity cases. We assumed that the worst case scenario would be a direct pass-through of all the nitrogen and argon not removed from the ASU to the transport system. This would be true for the low purity case, but an even more subdued effect would be anticipated for the mid and high purity cases in practice due to the inert gas removal systems. Despite this assumption however, the impact in Fig. 3 represents only a ~2% change in specific cost across the spectrum of ASU purity. This is much smaller than the delta between CO2 exit purity levels and should therefore not be regarded as a key parameter for future optimization efforts.

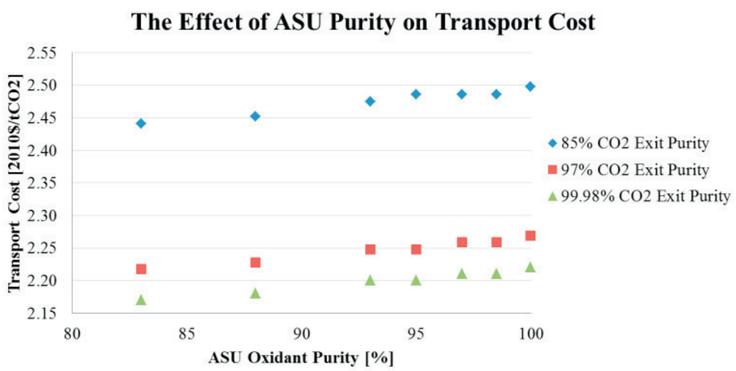

Fig.3. For 150 km distance theris very little variation in the specific transport cost for CO2 across the operational range of the ASU. The specific cost actually increases slightly due to reduced utilization of pipeline capacity.

3.4 Comparison of stochastic oxyfuel model with post-combustion capture

The prior presented parametric results indicated that avoidance costs were driven largely by the sulfur content of the coal being burned and the exit purity of the CO2 product. To assess the likelihood of oxyfuel being the most cost effective CCS option four stochastic scenarios were investigated: Illinois #6 and PRB with co-capture of SO2 and non-condensable gases and the same two coals operating at a CO2 exit purity of 99.5%. These four scenarios cover nearly the entirety of the exit purity v. coal composition decision space and therefore, when compared with an analogous post-combustion capture system, illuminate those areas where each technology has an advantage. A post-combustion capture system (99.5% CO2 exit purity) was modelled in the IECM v8.0 using an Amine FG+ solvent system on a super-critical pulverized coal plant firing the respective coal. The uncertainty in the cost and performance of oxyfuel resides predominantly with the ASU, CPU, and auxiliary flue gas desulfurization equipment. Consequently, for each scenario cost and performance multipliers for these critical pieces of equipment were varied stochastically along with the other variables presented in Table 1. For each oxyfuel scenario the @Risk v5.5 program was used to conduct 10,000 trials from which the cumulative distribution functions for levelized cost of electricity and avoidance cost presented in Figs. 4 and 5 were generated.

Table 1. Common variables and their distributions used in the co-capture and 99.5% CO2 exit purity Monte-Carlo simulations.

Variable Name	Distribution Type	Distribution Parameters
Net Plant Output [MW]	Static	550
Capacity Factor [%]	Static	75
Oxygen Purity [v/v%]	Static	95
CO2 Transport Distance [km]	Static	150
Excess Oxygen [%]	Uniform	5-15
SC Gross Heat Rate [kJ/kWh]	Uniform	8600-8900
ASU [kWh/tO2] Mult.	Triangle	0.9, 1.0, 1.1
ASU [2010$/kW-net] Mult.	Normal	1.0, 0.1
CPU [kWh/tCO2] Mult.	Triangle	0.9, 1.0, 1.1
CPU [2010$/kW-net] Mult.	Normal	1.0, 0.1
Aux. FGD [kW/tS-hr] Mult.	Uniform	0.5, 3.0
Aux. FGD [2010$/kW-net] Mult.	Uniform	0.5, 2.0

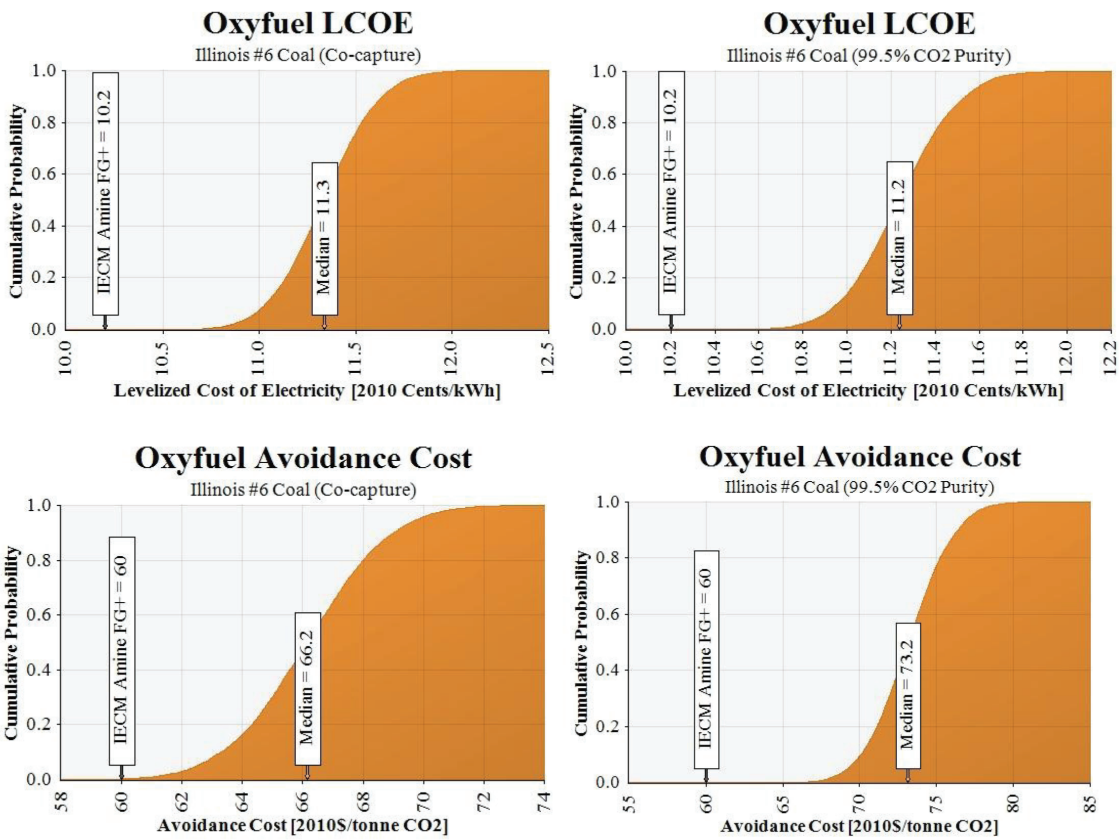

Fig. 4. From top to bottom are the LCOE and avoidance cost of a super-critical oxyfuel system firing Illinois #6 coal operated in co-capture mode and then producing CO2 product at a purity of 99.5% from left to right, respectively.

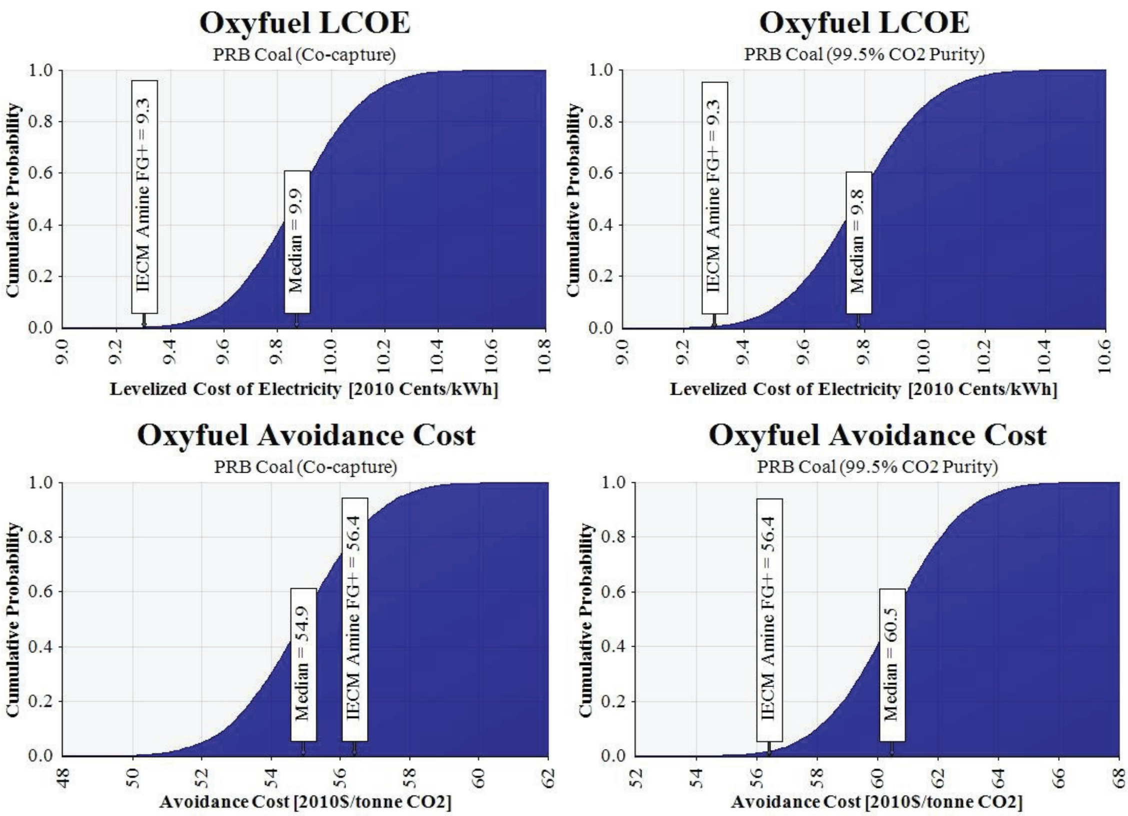

Fig. 5. From top to bottom are the LCOE and avoidance cost of a super-critical oxyfuel system firing PRB coal operated in co-capture mode and then producing a CO2 product purity of 99.5% from left to right, respectively.

None of the Illinois #6 fired scenarios produce a distribution which indicates that either the co-capture or 95% purity CO2 product cases have above a 1% change of producing electricity or avoiding carbon dioxide at a lower cost than the chosen Amine FG+ system. As expected [8,10] for both Illinois #6 and PRB; the avoidance cost is lower in the co-capture cases predominantly due to the entire flue gas stream being captured, thus spreading the added costs over a greater number of captured tonnes of carbon dioxide. As a consequence of this larger denominator affect the median avoided cost for the co-capture PRB case is actually lower than the Amine FG+ avoided cost despite having a higher LCOE. Collectively however, none of the case studies produce a median LCOE below the LCOE of the Amine FG+ system and only the co-capture PRB case produces avoidance costs which have an 80% chance of being equal to or less than those of a 99.5% purity Amine FG+ system.

3.5 Regional variation in anticipated oxyfuel electricity costs

The last point of inquiry for this analysis was to determine which areas of the United States were best positioned to have oxyfuel become a part of their low carbon generation portfolio if the political circumstances warrant such action. State specific information for coal usage [20] is kept by the EIA and includes information on both unit price and fuel composition. This was combined with a building construction cost index [21] kept by RS Means for the United States. Monte Carlo simulations were conducted using the cost index and EIA data for each state, where ample information was available, in order to generate an LCOE distribution. The median value of each distribution was then used to create the geographical representation in Fig. 6. Due to the uncertainty associated with transmission and storage costs, which are likely to vary substantially from state to state, a flat rate of 0.5₵ /kWh was used to cover these costs. This T&S sum is reflective of the 150 km modeled transmission costs from Fig. 3 and the costs estimates for terrestrial storage provided by IPCC [23]. States with proximity to the Powder River Basin, or are easily accessible by rail, display the lowest LCOE. The next lowest states are those which burn a large proportion of low sulfur coal or are still linked closely to the PRB by rail. As LCOE continues to rise the states which burn a larger percentage of high sulfur coal and those more geographically removed from the PRB fill in the lighter shades of the map.

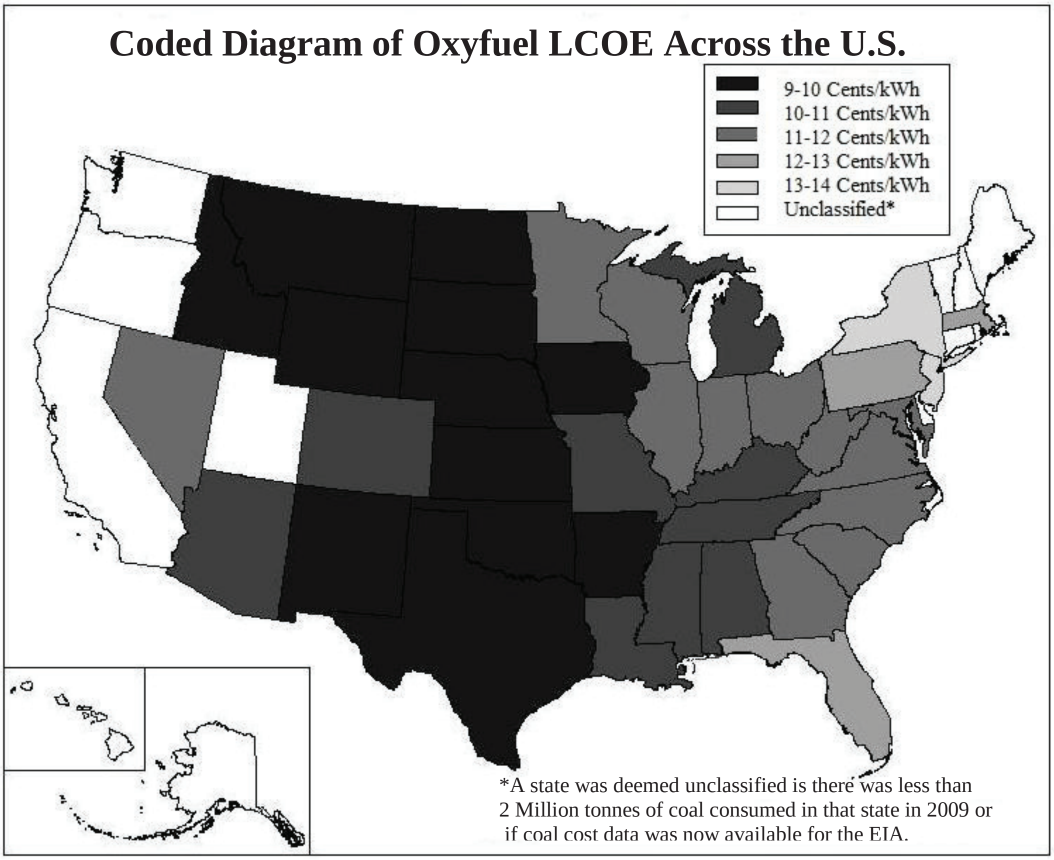

Fig.6. Oxyfuel LCOE Map of the United States [22] generated from EIA state inventory data for coal usage. Those areas with access to cheap, low sulfur coal appear most attractive for oxyfuel while those relying on more sulfur intensive varieties or are near the end of the coal distribution network fare less favorably.

4. Discussion

This study has evaluated several key system parameters affecting the operation of oxyfuel CCS plants in the United States. Results indicate that increasing restrictions on CO2 exit purity will translate directly to higher avoidance costs. Consequently, any future pipeline purity standards should seek to balance cost with safety concerns and storage capacity limitations. Oxidant purity presents a compromise between equipment downsizing and energy of separation which was identified to be optimized in the 95-97% oxygen range. The effect of oxidant purity on transportation cost is minor (~2%) compared to the effects of CO2 exit purity (~15%) but both represented changes to a cost which only amounts to about 5% of the total avoidance cost. The type of coal and the price paid per unit energy, which vary geographically, are extremely important factors in the LCOE and avoidance cost for oxyfuel plants. High-sulfur coals require additional gas processing equipment which results in additional equipment costs.

The results of the stochastic and parametric modeling presented here suggest that, with current technology, oxyfuel will be most cost-competitive with post-combustion capture systems for plants burning low-sulfur coals, and where co-capture of CO2 with SO2 and non-condensable gases is permitted. Future technological advances to improve the efficiency of the oxyfuel process such as the use of membranes, staged combustion techniques [24], or ion transport membranes [25,26] may serve to make the technology more appealing from a thermal efficiency perspective; but these improvements will do little to increase economic viability unless they simultaneously reduce the capital intensity of the installation. If all these improvements materialize in concert with evidence that the oxyfuel specific effluent removal systems are capable of adequate sulfur removal when operating with higher sulfur coals, then oxyfuel may well become the lowest cost option for carbon capture from pulverized coal plants given that co-capture is also permitted. To be transformative, further technological improvements must reduce the capital intensity of oxyfuel as a means of carbon capture.

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